

HIGH DISCHARGE CAPACITY LITHIUM BATTERY

BACKGROUND

This invention relates to electrochemical battery cells, particularly cells with a lithium negative electrode and an iron disulfide positive electrode.

5 Lithium batteries (batteries containing metallic lithium as the negative electrode active material) are becoming increasingly popular as portable power sources for electronic devices that have high power operating requirements. Common consumer lithium batteries include lithium/manganese dioxide (Li/MnO_2) and lithium/iron disulfide (Li/FeS_2) batteries, which have nominal voltages of 3.0 and 1.5 volts per cell, respectively.

10 Battery manufacturers are continually striving to design batteries with more discharge capacity. This can be accomplished by minimizing the volume in the cell taken up by the housing, including the seal and the vent, thereby maximizing the internal volume available for active materials. However, there will always be practical limitations on the maximum internal volume.

15 Another approach is to modify the internal cell design and materials to increase the discharge capacity. How to best accomplish this can depend at least in part on the discharge requirements of the devices to be powered by the batteries. For devices with low power requirements, the quantity of active materials tends to be very important, while for devices with high power requirements, discharge efficiencies tend to be more
20 important. Lithium batteries are often used in high power devices, since they are capable of excellent discharge efficiencies on high power discharge.

 In general, battery discharge efficiency decreases rapidly with increasing discharge power. Therefore, for high power providing high discharge efficiency is a priority. This often means using designs containing less active materials, thus sacrificing capacity on
25 low power and low rate discharge. For example, for good high power discharge efficiency, high interfacial surface area between the negative electrode (anode) and positive electrode (cathode) relative to the volume of the electrodes is desirable. This is often accomplished by using a spirally wound electrode assembly, in which relatively long, thin electrode strips are wound together in a coil. Unless the electrode compositions
30 have a high electrical conductivity, such long, thin electrodes typically require a current collector extending along much of the length and width of the electrode strip. The high interfacial surface area of the electrodes also means that more separator material is needed

to electrically insulate the positive and negative electrodes from each other. Because the maximum external dimensions are often set for the cells, either by industry standards or the size and shape of the battery compartments in equipment, increasing the electrode interfacial surface area also means having to reduce the amount of active electrode materials that can be used.

For batteries that are intended for both high and low power use, reducing cell active material inputs in order to maximize high power performance is less desirable than for batteries intended for only high power use. For example, AA size 1.5 volt Li/FeS₂ (FR6 size) batteries are intended for use in high power applications such as photoflash and digital still camera as well as general replacements for AA size 1.5 volt alkaline Zn/MnO₂ batteries, which are often used in lower power devices. In such situations it is important to maximize both high power discharge efficiency and cell input capacity. While it is generally desirable to maximize the electrode input capacity in any cell, the relative importance of doing so is greater in cells for lower power usage.

To maximize the active material inputs in the cell and mitigate the effects thereon of increasing the electrode interfacial surface area, it is desirable to use separator materials that take up as little internal volume in the cell as possible. There are practical limitations to doing so. The separator must be able to withstand the cell manufacturing processes without damage, provide adequate electrical insulation and ion transport between the anode and cathode and do so without developing defects resulting in internal short circuits between the anode and cathode when the cell is subjected to both normal and anticipated abnormal conditions of handling, transportation, storage and use.

Separator properties can be modified in a number of ways to improve the strength and resistance to damage. Examples are disclosed in U.S. Patent Nos. 5,952,120; 6,368,742; 5,667,911 and 6,602,593. However, changes made to increase strength can also adversely affect separator performance, based in part on factors such as cell chemistry, electrode design and features, cell manufacturing process, intended cell use, anticipated storage and use conditions, etc.

For certain cell chemistries maximizing the amounts of active materials in the cell can be more difficult. In lithium batteries, when the active cathode material reacts with the lithium to produce reaction products having a total volume greater than that of the reactants, swelling of the electrode assembly creates additional forces in the cell. These

forces can cause bulging of the cell housing and short circuits through the separator. Possible solutions to these problems include using strong (often thicker) materials for the cell housing and inert components within the cell, further limiting the internal volume available for active materials in cells with such active materials compared to cells with lower volume reaction products. For Li/FeS₂ cells another possible solution, disclosed in U.S. Patent No. 4,379,815, is to balance cathode expansion and anode contraction by mixing another active material with the FeS₂. Such active cathode materials include CuO, Bi₂O₃, Pb₂Bi₂O₅, P₃O₄, CoS₂ and mixtures thereof. However, adding other active materials to the cathode mixture can affect the electrical and discharge characteristics of the cell.

Just as battery manufacturers are continually trying to improve discharge capacity, they are also continually working to improve other battery characteristics, such as safety and reliability; making cells more resistant to internal short circuits can contribute to both. As is clear from the above discussion, changes made to improve resistance to internal short circuits can be counterproductive in maximizing discharge capacity.

In view of the above, an object of the present invention is to provide a lithium battery cell with increased discharge capacity. Another object of the invention is to provide a lithium battery cell with a high energy density (interfacial discharge capacity to interfacial electrode volume). Another object of the invention is to provide a Li/FeS₂ cell with a high interfacial electrode surface area that has increased discharge capacity on low power discharge without sacrificing discharge efficiency on high power discharge, preferably one with increased discharge capacity on both high rate and low rate discharge. Yet another object of the invention is to provide a Li/FeS₂ cell with increased cathode interfacial capacity and having both improved energy density and good resistance to internal short circuits.

SUMMARY

The above objects are met and the above disadvantages of the prior art are overcome by the present invention.

Accordingly, one aspect of the present invention is directed to an electrochemical battery cell comprising a housing; a negative electrode strip comprising metallic lithium, a positive electrode strip comprising an active material mixture and an electrolyte comprising at least one salt dissolved in a nonaqueous electrolyte disposed within the

housing; and a separator disposed between the negative and positive electrodes; the cell having a ratio of a cathode interfacial capacity to an electrode assembly interfacial volume of at least 710 mAh/cm³.

Another aspect of the present invention is directed to an electrochemical battery cell comprising a housing; a negative electrode, a positive electrode and an electrolyte disposed within the housing; and a separator disposed between the negative and positive electrodes. The housing comprises a cylindrical container with an integral closed bottom end, an initially open top end, a side wall extending between the bottom and top ends and a cover disposed in the top end to close the cell; the negative electrode is in the form of a strip with two opposing major surfaces and comprises metallic lithium; the positive electrode is in the form of a strip with two opposing major surfaces and comprises an active material mixture, the active material comprising greater than 50 weight percent iron disulfide; the electrolyte comprises one or more salts dissolved in a nonaqueous organic solvent; the negative and positive electrodes and the separator form a spiral wound cylindrical electrode assembly, with a radial outer surface disposed adjacent an inner surface of the container side wall; the electrode assembly has an interfacial volume; the positive electrode has an interfacial capacity; a ratio of the positive electrode interfacial capacity to the electrode assembly interfacial volume is at least 710 mAh/cm³; and the separator is a microporous membrane comprising polyethylene, with a machine direction and a transverse direction, an average thickness less than 22 μm and a tensile stress of at least 1.0 kgf/cm in both the machine direction and the transverse direction.

Another aspect of the present invention is directed to an electrochemical battery cell comprising a housing; a negative electrode, a positive electrode and an electrolyte disposed within the housing; and a separator disposed between the negative and positive electrodes. The cell is a cylindrical FR6 type Li/FeS₂ cell with a spiral wound electrode assembly having an electrode assembly interfacial volume; the cell has an interfacial capacity of at least 3500 mAh; the separator is a microporous membrane comprising polyethylene and has an average thickness less than 22 μm, a tensile stress of at least 2.0 kgf/cm in both a machine direction and a transverse direction, a dielectric breakdown voltage of at least 2400 volts, a maximum effective pore size of 0.08 μm to 0.20 μm and a BET specific surface area of 4.0 to 15 m²/g.

Yet another aspect of the present invention is directed to an electrochemical battery cell comprising a housing; a negative electrode, a positive electrode and an electrolyte disposed within the housing; and a separator disposed between the negative and positive electrodes. The cell is a cylindrical FR6 type Li/FeS₂ cell with a spiral wound electrode assembly having an electrode assembly interfacial volume; the separator is a microporous membrane comprising polyethylene and has an average thickness less than 22 μm, a tensile stress of at least 2.0 in both a machine direction and a transverse direction, a dielectric breakdown voltage of at least 2400 volts and a maximum effective pore size of 0.08 μm to 0.20 μm; the positive electrode comprises an active material comprising at least 95 weight percent iron disulfide; and the cell is capable of providing a discharge capacity of at least 2950 mAh when discharged at 200 mA continuously to 1.0 volt and a discharge capacity of at least 2600 mAh when discharged at 1000 mA continuously to 1.0 volt.

These and other features, advantages and objects of the present invention will be further understood and appreciated by those skilled in the art by reference to the following specification, claims and appended drawings.

Unless otherwise specified, as used herein the terms listed below are defined as follows:

- active material – one or more chemical compounds that are part of the discharge reaction of a cell and contribute to the cell discharge capacity, including impurities and small amounts of other moieties present;
- active material mixture – a mixture of solid electrode materials, excluding current collectors and electrode leads, that contains the electrode active material;
- capacity, discharge – the actual capacity delivered by a cell during discharge, generally expressed in amp-hour (Ah) or milliamp-hours (mAh);
- capacity, input – the theoretical capacity of an electrode, equal to the weight of each active material in the electrode times the theoretical specific capacity of that active material, where the theoretical specific capacity of each active material is determined according to the following calculation:

$$[(96,487 \text{ ampere-seconds/mole})/(\text{number of grams/mole of active material})] \\ \times (\text{number of electrons/mole of active material})/(3600 \text{ seconds/hour}) \\ \times (1000 \text{ milliampere hours/ampere-hour})$$

(e.g., Li = 3862.0 mAh/g, S = 1672.0 mAh/g, FeS₂ = 893.6 mAh/g, CoS₂ = 871.3 mAh/g, CF_x = 864.3 mAh/g, CuO = 673.8 mAh/g, C₂F = 623.0 mAh/g, FeS = 609.8 mAh/g, CuS = 560.7 mAh/g, Bi₂O₃ = 345.1 mAh/g, MnO₂ = 308.3 mAh/g, Pb₂Bi₂O₅ = 293.8 mAh/g and FeCuS₂ = 292.1 mAh/g);

- 5 • capacity, cell interfacial – the smaller of the negative and positive electrode capacity;
- capacity, electrode interfacial – the total contribution of an electrode to the cell theoretical discharge capacity, based on the overall cell discharge reaction mechanism(s) and the total amount of active material contained within the that portion of the active material mixture adjacent to active material in the opposite electrode, assuming complete reaction of all of the active material, generally expressed in Ah or mAh (where only one of the two major surfaces of an electrode strip is adjacent active material in the opposite electrode, only the active material on that side of the electrode – either the material on that side of a solid current collector sheet or that material in half the thickness of an electrode without a solid current collector sheet – is included in the determination of interfacial capacity);
- 10 • electrode assembly – the combination of the negative electrode, positive electrode, and separator, as well as any insulating materials, overwraps, tapes, etc., that are incorporated therewith, but excluding any separate electrical lead affixed to the active material, active material mixture or current collector;
- 20 • electrode loading – active material mixture dry weight per unit of electrode surface area, generally expressed in grams per square centimeter (g/cm²);
- electrode packing – active material dry weight per unit of electrode surface area divided by the theoretical active material mixture dry weight per unit of electrode surface area, based on the real densities of the solid materials in the mixture, generally expressed as a percentage;
- 25 • folded electrodes – electrode strips that are combined into an assembly by folding, with the lengths of the strips either parallel to or crossing one another;
- interfacial height, electrode assembly – the average height, parallel to the longitudinal axis of the cell, of the interfacial surface of the electrodes in the assembly;
- 30 • interfacial volume, electrode assembly – the volume within the cell housing defined by the cross-sectional area, perpendicular to the longitudinal axis of the cell, at the inner surface of the container side wall(s) and the electrode assembly interfacial height;

- nominal – a value, specified by the manufacturer, that is representative of what can be expected for that characteristic or property;
- percent discharge – the percentage of the rated capacity removed from a cell during discharge;
- 5 • spiral wound electrodes – electrode strips that are combined into an assembly by winding along their lengths or widths, e.g., around a mandrel or central core; and
- void volume, electrode assembly – the volume of the electrode assembly voids per unit of interfacial height, determined by subtracting the sum of the volumes of the non-porous electrode assembly components and the solid portions of the porous electrode
- 10 assembly components contained within the interfacial height from the electrode assembly interfacial volume (microporous separators, insulating films, tapes, etc. are assumed to be non-porous and non-compressible, and volume of a porous electrode is determined using the real densities of the components and the total actual volume), generally expressed in cm^3/cm .

15

BRIEF DESCRIPTION OF THE DRAWINGS

In the drawings:

Fig. 1 is an embodiment of the electrochemical battery cell of the invention; and

20 Fig. 2 is a graph showing Impact Test results for partially discharged FR6 cells as a function of the volume of voids per unit height of the electrode assembly within the interfacial height.

DESCRIPTION

25 The battery cell of the invention has an anode comprising metallic lithium as the negative electrode active material. The anode and cathode are both in the form of strips, which are joined together in an electrode assembly to provide a high interfacial surface area relative to the volumes of the electrodes containing active material. The higher the interfacial surface area, the lower the current density and the better the cell's capability to deliver high power on discharge. The cell also has a high ratio of cathode interfacial

30 capacity to electrode assembly interfacial volume – at least 710 mAh/cm^2 . This means that the volume of active materials in the electrode assembly is high, to provide a high discharge capacity. The high volume of active materials can be achieved by controlling a number of variables, including: the ratio of interfacial input capacity to total input

capacity, the volume of the cathode current collector, the concentration of active cathode material in the cathode mixture and the volume of separator in the electrode assembly.

The invention will be better understood with reference to Fig. 1, which shows an embodiment of a cell according to the invention. Cell 10 is an FR6 type cylindrical Li/FeS₂ battery cell. Cell 10 has a housing that includes a can 12 with a closed bottom and an open top end that is closed with a cell cover 14 and a gasket 16. The can 12 has a bead or reduced diameter step near the top end to support the gasket 16 and cover 14. The gasket 16 is compressed between the can 12 and the cover 14 to seal an anode 18, a cathode 20 and electrolyte within the cell 10. The anode 18, cathode 20 and a separator 26 are spirally wound together into an electrode assembly. The cathode 20 has a metal current collector 22, which extends from the top end of the electrode assembly and is connected to the inner surface of the cover 14 with a contact spring 24. The anode 18 is electrically connected to the inner surface of the can 12 by a metal tab (not shown). An insulating cone 46 is located around the peripheral portion of the top of the electrode assembly to prevent the cathode current collector 22 from making contact with the can 12, and contact between the bottom edge of the cathode 20 and the bottom of the can 12 is prevented by the inward-folded extension of the separator 26 and an electrically insulating bottom disc 44 positioned in the bottom of the can 12. Cell 10 has a separate positive terminal cover 40, which is held in place by the inwardly crimped top edge of the can 12 and the gasket 16. The can 12 serves as the negative contact terminal. Disposed between the peripheral flange of the terminal cover 40 and the cell cover 14 is a positive temperature coefficient (PTC) device 42 that substantially limits the flow of current under abusive electrical conditions. Cell 10 also includes a pressure relief vent. The cell cover 14 has an aperture comprising an inward projecting central vent well 28 with a vent hole 30 in the bottom of the well 28. The aperture is sealed by a vent ball 32 and a thin-walled thermoplastic bushing 34, which is compressed between the vertical wall of the vent well 28 and the periphery of the vent ball 32. When the cell internal pressure exceeds a predetermined level, the vent ball 32, or both the ball 32 and bushing 34, is forced out of the aperture to release pressurized gases from the cell 10.

The cell container is often a metal can with an integral closed bottom, though a metal tube that is initially open at both ends may also be used instead of a can. The can is generally steel, plated with nickel on at least the outside to protect the outside of the can

from corrosion. The type of plating can be varied to provide varying degrees of corrosion resistance or to provide the desired appearance. The type of steel will depend in part on the manner in which the container is formed. For drawn cans the steel can be a diffusion annealed, low carbon, aluminum killed, SAE 1006 or equivalent steel, with a grain size of
5 ASTM 9 to 11 and equiaxed to slightly elongated grain shape. Other steels, such as stainless steels, can be used to meet special needs. For example, when the can is in electrical contact with the cathode, a stainless steel may be used for improved resistance to corrosion by the cathode and electrolyte.

The cell cover is typically metal. Nickel plated steel may be used, but a stainless
10 steel is often desirable, especially when the cover is in electrical contact with the cathode. The complexity of the cover shape will also be a factor in material selection. The cell cover may have a simple shape, such as a thick, flat disk, or it may have a more complex shape, such as the cover shown in Fig. 1. When the cover has a complex shape like that in Fig. 1, a type 304 soft annealed stainless steel with ASTM 8-9 grain size may be used, to
15 provide the desired corrosion resistance and ease of metal forming. Formed covers may also be plated, with nickel for example.

The terminal cover should have good resistance to corrosion by water in the ambient environment, good electrical conductivity and, when visible on consumer batteries, an attractive appearance. Terminal covers are often made from nickel plated
20 cold rolled steel or steel that is nickel plated after the covers are formed. Where terminals are located over pressure relief vents, the terminal covers generally have one or more holes to facilitate cell venting.

The gasket is made from any suitable thermoplastic material that provides the desired sealing properties. Material selection is based in part on the electrolyte
25 composition. Examples of suitable materials include polypropylene, polyphenylene sulfide, tetrafluoride-perfluoroalkyl vinyl ether copolymer, polybutylene terephthalate and combinations thereof. Preferred gasket materials include polypropylene (e.g., PRO-FAX® 6524 from Basell Polyolefins, Wilmington, DE, USA), polybutylene terephthalate (e.g., CELANEX® PBT, grade 1600A from Ticona-US, Summit, NJ, USA) and
30 polyphenylene sulfide (e.g., TECHTRON® PPS from Boedeker Plastics, Inc., Shiner, TX, USA). Small amounts of other polymers, reinforcing inorganic fillers and/or organic compounds may also be added to the base resin of the gasket.

The gasket may be coated with a sealant to provide the best seal. Ethylene propylene diene terpolymer (EPDM) is a suitable sealant material, but other suitable materials can be used.

5 The vent bushing is made from a thermoplastic material that is resistant to cold flow at high temperatures (e.g., 75°C). The thermoplastic material comprises a base resin such as ethylene-tetrafluoroethylene, polybutylene terephthalate, polyphenylene sulfide, polyphthalamide, ethylene-chlorotrifluoroethylene, chlorotrifluoroethylene, perfluoroalkoxyalkane, fluorinated perfluoroethylene polypropylene and polyetherether ketone. Ethylene-tetrafluoroethylene copolymer (ETFE), polyphenylene sulfide (PPS),
10 polybutylene terephthalate (PBT) and polyphthalamide are preferred. The resin can be modified by adding a thermal-stabilizing filler to provide a vent bushing with the desired sealing and venting characteristics at high temperatures. The bushing can be injection molded from the thermoplastic material. TEFZEL® HT2004 (ETFE resin with 25 weight percent chopped glass filler) is a preferred thermoplastic material.

15 The vent ball can be made from any suitable material that is stable in contact with the cell contents and provides the desired cell sealing and venting characteristic. Glasses or metals, such as stainless steel, can be used.

The anode comprises a strip of lithium metal, sometimes referred to as lithium foil. The composition of the lithium can vary, though for battery grade lithium the purity is
20 always high. The lithium can be alloyed with other metals, such as aluminum, to provide the desired cell electrical performance. Battery grade lithium-aluminum foil containing 0.5 weight percent aluminum is available from Chemetall Foote Corp., Kings Mountain, NC, USA.

The anode may have a current collector, within or on the surface of the metallic
25 lithium. As in the cell in Fig. 1, a separate current collector may not be needed, since lithium has a high electrical conductivity, but a current collector may be included, e.g., to maintain electrical continuity within the anode during discharge, as the lithium is consumed. When the anode includes a current collector, it may be made of copper because of its conductivity, but other conductive metals can be used as long as they are
30 stable inside the cell.

A thin metal strip often serves as an electrical lead, or tab, connecting the anode to one of the cell terminals (the can in the case of the FR6 cell shown in Fig. 1). The metal

strip is often made from nickel or nickel plated steel and affixed directly to the lithium. This may be accomplished embedding an end of the lead within a portion of the anode or by simply pressing an end of the lead onto the surface of the lithium foil.

The cathode is in the form of a strip that comprises a current collector and a mixture that includes one or more electrochemically active materials, usually in particulate form. Iron disulfide (FeS_2) is a preferred active material. In a Li/FeS_2 cell the active material comprises greater than 50 weight percent FeS_2 . The cathode can also contain one or more additional active materials, depending on the desired cell electrical and discharge characteristics. The additional active cathode material may be any suitable active cathode material. Examples include Bi_2O_3 , C_2F , CF_x , $(\text{CF})_n$, CoS_2 , CuO , CuS , FeS , FeCuS_2 , MnO_2 , $\text{Pb}_2\text{Bi}_2\text{O}_5$ and S . More preferably the active material for a Li/FeS_2 cell cathode comprises at least 95 weight percent FeS_2 , yet more preferably at least 99 weight percent FeS_2 , and most preferably FeS_2 is the sole active cathode material. Battery grade FeS_2 having a purity level of at least 95 weight percent is available from American Minerals, Inc., Camden, NJ, USA; Chemetall GmbH, Vienna, Austria; and Kyanite Mining Corp., Dillwyn, VA, USA.

In addition to the active material, the cathode mixture contains other materials. A binder is generally used to hold the particulate materials together and adhere the mixture to the current collector. One or more conductive materials such as metal, graphite and carbon black powders may be added to provide improved electrical conductivity to the mixture. The amount of conductive material used can be dependent upon factors such as the electrical conductivity of the active material and binder, the thickness of the mixture on the current collector and the current collector design. Small amounts of various additives may also be used to enhance cathode manufacturing and cell performance. The following are examples of active material mixture materials for Li/FeS_2 cell cathodes. Graphite: KS-6 and TIMREX® MX15 grades synthetic graphite from Timcal America, Westlake, OH, USA. Carbon black: Grade C55 acetylene black from Chevron Phillips Company LP, Houston, TX, USA. Binder: ethylene/propylene copolymer (PEPP) made by Polymont Plastics Corp. (formerly Polysar, Inc.) and available from Harwick Standard Distribution Corp., Akron, OH, USA; non-ionic water soluble polyethylene oxide (PEO): POLYOX® from Dow Chemical Company, Midland, MI, USA; and G1651 grade styrene-ethylene/butylenes-styrene (SEBS) block copolymer from Kraton Polymers,

Houston, TX. Additives: FLUO HT ® micronized polytetrafluoroethylene (PTFE) manufactured by Micro Powders Inc., Tarrytown, NY, USA (commercially available from Dar-Tech Inc., Cleveland, OH, USA) and AEROSIL® 200 grade fumed silica from Degussa Corporation Pigment Group, Ridgefield, NJ.

5 The current collector may be disposed within or imbedded into the cathode surface, or the cathode mixture may be coated onto one or both sides of a thin metal strip. Aluminum is a commonly used material. The current collector may extend beyond the portion of the cathode containing the cathode mixture. This extending portion of the current collector can provide a convenient area for making contact with the electrical lead
10 connected to the positive terminal. It is desirable to keep the volume of the extending portion of the current collector to a minimum to make as much of the internal volume of the cell available for active materials and electrolyte.

 A preferred method of making FeS₂ cathodes is to roll coat a slurry of active material mixture materials in a highly volatile organic solvent (e.g., trichloroethylene)
15 onto both sides of a sheet of aluminum foil, dry the coating to remove the solvent, calender the coated foil to compact the coating, slit the coated foil to the desired width and cut strips of the slit cathode material to the desired length. It is desirable to use cathode materials with small particle sizes to minimize the risk of puncturing the separator. For example, FeS₂ is preferably sieved through a 230 mesh (62 µm) screen before use.

20 The cathode is electrically connected to the positive terminal of the cell. This may be accomplished with an electrical lead, often in the form of a thin metal strip or a spring, as shown in Fig. 1. The lead is often made from nickel plated stainless steel.

 The separator is a thin microporous membrane that is ion-permeable and electrically nonconductive. It is capable of holding at least some electrolyte within the
25 pores of the separator. The separator is disposed between adjacent surfaces of the anode and cathode to electrically insulate the electrodes from each other. Portions of the separator may also insulate other components in electrical contact with the cell terminals to prevent internal short circuits. Edges of the separator often extend beyond the edges of at least one electrode to insure that the anode and cathode do not make electrical contact
30 even if they are not perfectly aligned with each other. However, it is desirable to minimize the amount of separator extending beyond the electrodes.

To provide good high power discharge performance it is desirable that the separator have the characteristics (pores with a smallest dimension of at least 0.005 μm and a largest dimension of no more than 5 μm across, a porosity in the range of 30 to 70 percent, an area specific resistance of from 2 to 15 ohm-cm^2 and a tortuosity less than 2.5) disclosed in U.S. Patent No. 5,290,414, issued March 1, 1994, and hereby incorporated by reference. Suitable separator materials should also be strong enough to withstand cell manufacturing processes as well as pressure that may be exerted on the separator during cell discharge without tears, splits, holes or other gaps developing that could result in an internal short circuit.

To minimize the total separator volume in the cell, the separator should be as thin as possible, preferably less than 25 μm thick, and more preferably no more than 22 μm thick, such as 20 μm or 16 μm . Separators as thin as 10 μm or less can be used if they have suitable properties. The required thickness will depend in part on the strength of the separator material and the magnitude and location of forces that may be exerted on the separator where it provides electrical insulation.

A number of characteristics besides thickness can affect separator strength. One of these is tensile stress. A high tensile stress is desirable, preferably at least 800, more preferably at least 1000 kilograms of force per square centimeter (kgf/cm^2). Because of the manufacturing processes typically used to make microporous separators, tensile stress is typically greater in the machine direction (MD) than in the transverse direction (TD). The minimum tensile stress required can depend in part on the diameter of the cell. For example, for a FR6 type cell the preferred tensile stress is at least 1500 kgf/cm^2 in the machine direction and at least 1200 kgf/cm^2 in the transverse direction, and for a FR03 type cell the preferred tensile strengths in the machine and transverse directions are 1300 and 1000 kgf/cm^2 , respectively. If the tensile stress is too low, manufacturing and internal cell forces can cause tears or other holes. In general, the higher the tensile stress the better from the standpoint of strength. However, if the tensile stress is too high, other desirable properties of the separator may be adversely affected.

Tensile stress can also be expressed in kgf/cm , which can be calculated from tensile stress in kgf/cm^2 by multiplying the later by the separator thickness in cm. Tensile stress in kgf/cm is also useful for identifying desirable properties related to separator strength. Therefore, it is desirable that the separator have a tensile stress of at least 1.0

kgf/cm, preferably at least 1.5 kgf/cm and more preferably at least 1.75 kgf/cm in both the machine and transverse directions. For cells with diameters greater than about 0.45 inch (11.4 mm), a tensile stress of at least 2.0 kgf/cm is most preferable.

Another indicator of separator strength is its dielectric breakdown voltage.

- 5 Preferably the average dielectric breakdown voltage will be at least 2000 volts, more preferably at least 2200 volts. For cylindrical cells with a diameter greater than about 0.45 in (11.4 mm), the average dielectric breakdown voltage is most preferably at least 2400 volts. If the dielectric breakdown voltage is too low, it is difficult to reliably remove cells with defective or damaged separators by electrical testing (e.g., retention of a high voltage
10 applied to the electrode assembly before the addition of electrolyte) during cell manufacturing. It is desirable that the dielectric breakdown is as high as possible while still achieving other desirable separator properties.

- The average effective pore size is another of the more important indicators of separator strength. While large pores are desirable to maximize ion transport through the
15 separator, if the pores are too large the separator will be susceptible to penetration and short circuits between the electrodes. The preferred maximum effective pore size is from 0.08 μm to 0.40 μm , more preferably no greater than 0.20 μm .

- The BET specific surface area is also related to pore size, as well as the number of pores. In general, cell discharge performance tends to be better when the separator has a
20 higher specific surface area, but the separator strength tends to be lower. It is desirable for the BET specific surface area to be no greater than 40 m^2/g , but it is also desirable that it be at least 15 m^2/g , more preferably at least 25 m^2/g .

- For good high rate and high power cell discharge performance a low area specific resistance is desirable. Thinner separators tend to have lower resistances, but the separator
25 should also be strong enough, limiting how thin the separator can be. Preferably the area specific resistance is no greater than 4.3 $\text{ohm}\cdot\text{cm}^2$, more preferably no greater than 4.0 $\text{ohm}\cdot\text{cm}^2$, and most preferably no greater than 3.5 $\text{ohm}\cdot\text{cm}^2$.

- Separator membranes for use in lithium batteries are often made of polypropylene, polyethylene or ultrahigh molecular weight polyethylene, with polyethylene being
30 preferred. The separator can be a single layer of biaxially oriented microporous membrane, or two or more layers can be laminated together to provide the desired tensile strengths in orthogonal directions. A single layer is preferred to minimize the cost.

Suitable single layer biaxially oriented polyethylene microporous separator is available from Tonen Chemical Corp., available from EXXON Mobile Chemical Co., Macedonia, NY, USA. Setela F20DHI grade separator has a 20 μm nominal thickness, and Setela 16MMS grade has a 16 μm nominal thickness.

5 The anode, cathode and separator strips are combined together in an electrode assembly. The electrode assembly may be a spirally wound design, such as that shown in Fig. 1, made by winding alternating strips of cathode, separator, anode and separator around a mandrel, which is extracted from the electrode assembly when winding is complete. At least one layer of separator and/or at least one layer of electrically insulating
10 film (e.g., polypropylene) is generally wrapped around the outside of the electrode assembly. This serves a number of purposes: it helps hold the assembly together and may be used to adjust the width or diameter of the assembly to the desired dimension. The outermost end of the separator or other outer film layer may be held down with a piece of adhesive tape or by heat sealing.

15 Rather than being spirally wound, the electrode assembly may be formed by folding the electrode and separator strips together. The strips may be aligned along their lengths and then folded in an accordion fashion, or the anode and one electrode strip may be laid perpendicular to the cathode and another electrode strip and the electrodes alternately folded one across the other (orthogonally oriented), in both cases forming a
20 stack of alternating anode and cathode layers.

 The electrode assembly is inserted into the housing container. In the case of a spirally wound electrode assembly, whether in a cylindrical or prismatic container, the major surfaces of the electrodes are perpendicular to the side wall(s) of the container (in other words, the central core of the electrode assembly is parallel to a longitudinal axis of
25 the cell). Folded electrode assemblies are typically used in prismatic cells. In the case of an accordion-folded electrode assembly, the assembly is oriented so that the flat electrode surfaces at opposite ends of the stack of electrode layers are adjacent to opposite sides of the container. In these configurations the majority of the total area of the major surfaces of the anode is adjacent the majority of the total area of the major surfaces of the cathode
30 through the separator, and the outermost portions of the electrode major surfaces are adjacent to the side wall of the container. In this way, expansion of the electrode assembly

due to an increase in the combined thicknesses of the anode and cathode is constrained by the container side wall(s).

A nonaqueous electrolyte, containing water only in very small quantities as a contaminant (e.g., no more than about 500 parts per million by weight, depending on the electrolyte salt being used), is used in the battery cell of the invention. Any nonaqueous electrolyte suitable for use with lithium and active cathode material may be used. The electrolyte contains one or more electrolyte salts dissolved in an organic solvent. For a Li/FeS₂ cell examples of suitable salts include lithium bromide, lithium perchlorate, lithium hexafluorophosphate, potassium hexafluorophosphate, lithium hexafluoroarsenate, lithium trifluoromethanesulfonate and lithium iodide; and suitable organic solvents include one or more of the following: dimethyl carbonate, diethyl carbonate, methylethyl carbonate, ethylene carbonate, propylene carbonate, 1,2-butylene carbonate, 2,3-butylene carbonate, methyl formate, γ -butyrolactone, sulfolane, acetonitrile, 3,5-dimethylisoxazole, n,n-dimethyl formamide and ethers. The salt/solvent combination will provide sufficient electrolytic and electrical conductivity to meet the cell discharge requirements over the desired temperature range. Ethers are often desirable because of their generally low viscosity, good wetting capability, good low temperature discharge performance and good high rate discharge performance. This is particularly true in Li/FeS₂ cells because the ethers are more stable than with MnO₂ cathodes, so higher ether levels can be used. Suitable ethers include, but are not limited to acyclic ethers such as 1,2-dimethoxyethane, 1,2-diethoxyethane, di(methoxyethyl)ether, triglyme, tetraglyme and diethyl ether; and cyclic ethers such as 1,3-dioxolane, tetrahydrofuran, 2-methyl tetrahydrofuran and 3-methyl-2-oxazolidinone.

Specific anode, cathode and electrolyte compositions and amounts can be adjusted to provide the desired cell manufacturing, performance and storage characteristics.

The cell can be closed and sealed using any suitable process. Such processes may include, but are not limited to, crimping, redrawing, colletting and combinations thereof. For example, for the cell in Fig. 1, a bead is formed in the can after the electrodes and insulator cone are inserted, and the gasket and cover assembly (including the cell cover, contact spring and vent bushing) are placed in the open end of the can. The cell is supported at the bead while the gasket and cover assembly are pushed downward against the bead. The diameter of the top of the can above the bead is reduced with a segmented

collet to hold the gasket and cover assembly in place in the cell. After electrolyte is dispensed into the cell through the apertures in the vent bushing and cover, a vent ball is inserted into the bushing to seal the aperture in the cell cover. A PTC device and a terminal cover are placed onto the cell over the cell cover, and the top edge of the can is bent inward with a crimping die to hold retain the gasket, cover assembly, PTC device and terminal cover and complete the sealing of the open end of the can by the gasket.

The above description is particularly relevant to cylindrical Li/FeS₂ cells, such as FR6 and FR03 types, as defined in International Standards IEC 60086-1 and IEC 60086-2, published by the International Electrotechnical Commission, Geneva, Switzerland.

However, the invention may also be adapted to other cell sizes and shapes and to cells with other electrode assembly, housing, seal and pressure relief vent designs.

Features invention and its advantages are further illustrated in the following examples.

Example 1

FR6 type cylindrical Li/FeS₂ cells with spirally wound electrode assemblies were made with varying electrode assembly void volumes per centimeter of interfacial electrode assembly height over a range of about 0.373 to about 0.455 cm³/cm. The void volumes were varied by adjusting the volume of the voids within the active material mixture coated on the cathode. This was done with various combinations of mixture formulations, thickness and packing. The separator material used in all cells was a highly crystalline, uniaxially oriented, microporous polypropylene material with a 25 μm nominal thickness.

Example 2

Samples of the cells from Example 1 were prepared for testing. For each group with a given void volume per unit of height, some cells remained undischarged and some cells were 50% discharged (discharged at a rate of 200 mA for the time required to remove 50 percent of the rated capacity). Undischarged and 50% discharged cells were tested on an Impact Test, and the external temperature of each of the cells tested was monitored during and for six hours after testing.

For the Impact Test a sample cell is placed on a flat surface, a 15.8 mm diameter bar is placed across the center of the sample, and a 9.1 kg mass is dropped from a height of 61 ± 2.5 cm onto the sample. The sample cell is impacted with its longitudinal axis

parallel to the flat surface and perpendicular to the longitudinal axis of the 15.8 mm diameter bar lying across the center of the cell. Each sample is subjected to only a single impact.

None of the undischarged cells had an external temperature that exceeded 170°C.

- 5 The percentage of 50% discharged cells whose external temperatures exceeded 170°C was plotted. The best curve fitting the plotted points is shown in Fig. 2, where the void volume per unit height (in cm^3/cm) is on the x-axis, and the percentage of cells with an external temperature exceeding 170°C is on the y-axis.

- 10 The Impact Test results show that as the electrode assembly void volume decreases, the percentage of cells with an external temperature exceeding 170°C increases. From the graph in Fig. 2, 0% of the cells with a void volume of approximately 0.45 cm^3/cm of interfacial height would be predicted to have an external temperature exceeding 170°C, and over 60% with a void volume of approximately 0.37 cm^3/cm would be predicted to exceed 170°C. The high external temperatures were attributed to damage to
15 the separator resulting in heat-generating internal short circuits.

- Subsequent examination of both FR6 Li/FeS₂ cells after different levels of discharge revealed that a net increase in the FR6 cell total electrode volume, which becomes greater as discharge proceeds, causes bending and buckling of the electrode strips and collapsing of the central core of the electrode assembly by the time the cells are 50%
20 discharged. In contrast, similar examination of Li/MnO₂ cells with spirally wound electrodes showed little if any discernable change in the electrode assembly at 50% discharge. The difference between the active material volumes and the volumes of the discharge reaction products provides an explanation for the difference in the effects of discharge on the spirally wound electrode assemblies of Li/FeS₂ vs. Li/MnO₂ cells.

25

Example 3

- Four lots of FR6 cells were made, each with a separator made from a different material. A description of the separator materials is provided in Table 1, and typical separator properties, as determined by the methods described below, are summarized in
30 Table 2. The separator material used for Lot A is the same as that used in the cells in Example 1. Each cell contained about 1.60 g of electrolyte, the electrolyte consisting of 9.14 weight percent LiI salt in a solvent blend of 1,3-dioxolane, 1,2-dimethoxyethane and 3,5-dimethylisoxazole (63.05 : 27.63 : 0.18 by weight).

Table 1

Lot A	Lot B	Lot C	Lot D
highly crystalline uniaxially oriented microporous polypropylene 25 μm thick	highly crystalline uniaxially oriented microporous polypropylene 20 μm thick	amorphous biaxially oriented microporous ultrahigh molecular weight polyethylene 20 μm thick	amorphous biaxially oriented microporous polyethylene 20 μm thick

Table 2

Property (units)	Lot A	Lot B	Lot C	Lot D
Porosity (%)	38	38	42	40
Max. effective pore size (μm)	0.10	0.06	0.38	0.10
Dielectric breakdown volt. (V)	2700	2200	1600	2625
Tensile stress, TD (kgf/cm^2)	190	162	844	1336
Tensile stress, TD (kgf/cm)	0.475	0.324	1.688	2.672
Tensile stress, MD (kgf/cm^2)	1687	2671	1541	1828
Tensile stress, MD (kgf/cm)	4.218	5.342	3.082	3.656
Tensile elongation, TD (%)	1000	790	440	320
Tensile elongation, MD (%)	120	54	260	225
Area specific resist. ($\Omega\text{-cm}^2$)	4.59	2.71	3.06	2.90
BET spec. surf. area (m^2/g)	44.0	48.9	16.2	36.4

5

The same cell design was used for all of Lots A-D. The cell design was one with greater amounts of active materials, a higher concentration of FeS_2 in the cathode mixture and an increased electrode interfacial surface area, as well as a lower anode : cathode total input capacity ratio, than cells from Example 1 with an electrode assembly void volume to interfacial height ratio of about 0.452, resulting in a 22 percent increase in the cell interfacial capacity.

10

Example 4

Cells from each lot in Example 3 were discharged 50% and then tested on the Impact Test. The percentage of cells exceeding 170°C on the test was 20% for Lot A, 80% for Lot B and 0% for Lots C and D.

15

By increasing the interfacial capacity 22 percent compared to cells from Example 1 with an electrode assembly void volume to interfacial height ratio of about 0.452, the percentage of cells exceeding 170°C on the Impact Test increased from 0% to 20%. Cells

Table 3

Feature	Lot D	Lot E	Lot F
Anode	Li-Al	Li-Al	Li-Al
Li foil thickness (cm)	0.01524	0.01524	0.01524
Li foil width (cm)	3.899	3.899	3.861
Li foil cut length (cm)	31.50	30.48	30.61
Li foil weight (g)	0.99	0.97	0.95
Li input capacity/cell (mAh)	3859	3735	3664
Anode interfacial capacity/cell (mAh)	3600	3485	3470
Cathode			
Al current collector thickness (cm)	0.00254	0.00254	0.00254
Current collector volume (cm ³)	0.3313	0.3199	0.3186
Dry coating (wt%): FeS ₂	92.00	92.00	92.75
acetylene black	1.40	1.40	2.5
graphite	4.00 MX15	4.0 MX15	2.25 KS6
binder	2.00 SEBS	2.0 SEBS	2.00 PEPP
other	0.3 PTFE	0.3 PTFE	0.05 PEO
other	0.3 silica	0.3 silica	
Coating real density (g/cm ³)	4.115	4.115	4.116
Coating thickness (ea. side) (cm)	0.0080	0.0080	0.0072
Coating loading (mg/cm ²)	21.26	21.26	16.98
Coating packing (%)	64	64	57
Coating width (cm)	4.077	4.077	4.039
Cathode (coating) length (cm)	29.85	28.83	28.96
Coating weight/cell (g)	5.17	5.00	3.97
Cathode input capacity/cell (mAh)	4250	4110	3290
Cathode interfacial capacity/cell (mAh)	4005	3877	3105
Separator (2 pieces/cell)			
Material	20 μ m PE	25 μ m PP	25 μ m PP
Length/piece (cm)	39.5	39	39
Width/piece (cm)	44	44	44
Total volume (cm ³)	0.431	0.425	0.532
Electrode Assembly			
Winding mandrel diameter (cm)	0.4	0.4	0.4
Overwrap volume (cm ³)	0.124	0.124	0.124
Interfacial height (cm)	3.899	3.899	3.861
Can	Ni pltd. steel	Ni pltd. steel	Ni pltd. steel
Thickness (cm)	0.0241	0.0241	0.0241
Outside diameter (cm)	1.392	1.392	1.379
Inside diameter (cm)	1.344	1.344	1.331
Cell			
Internal void volume (%)	10	10	12
Anode/cathode input capacity	0.95	0.95	1.18
Interfacial capacity (mAh)	3600	3485	3105
Cathode cap./interfac. vol. (mAh/cm ³)	724	701	578

Example 6

Cells from each of Lots D, E and F were discharged at 200 mA continuously to 1.0 volt and at 1000 mA continuously to 1.0 volt. Table 4 compares the results.

5 Table 4

Test	Lot D	Lot E	Lot F
200 mA	3040 mAh	2890 mAh	2417 mAh
1000 mA	2816 mAh	2170 mAh	2170 mAh

The following separator material properties are determined according to the corresponding methods. Unless otherwise specified, all disclosed properties are as determined at room temperature (20-25°C).

- Tensile stress was determined using an Instron Model 1123 Universal Tester according to ASTM D882-02. Samples were cut to 0.50 inches (1.27 cm) by 1.75 inches (4.45 cm). The initial jaw separation was 1 inch (2.54 cm) and the strain rate was 2 inches (5.08 cm) per minute. Tensile stress was calculated as applied force divided by the initial cross sectional area (the width of the sample perpendicular to the applied force times the thickness of the sample).
- Maximum effective pore diameter was measured on images made at 30,000 times magnification using a Scanning Electron Microscope and covering an area of 4 μm x 3 μm . For each separator sample, an image was made of both major surfaces. On each image, the largest pores were measured to determine the largest round diameter that would fit within the pore wall (the maximum effective diameter of the individual pores). The maximum effective pore diameter of the sample was calculated by averaging the maximum effective pore diameters of the two largest pores on each side (i.e., the average of four individual pores).
- Porosity was determined by (1) cutting a sample of the separator, (2) weighing the sample, (3) measuring the length, width, and thickness of the sample, (3) calculating the density from the weight and measurements, (4) dividing the calculated density by the theoretical density of the separator polymer resin, as provided by the separator manufacturer, (5) multiplying the dividend by 100, and (5) subtracting this value from 100.

- Dielectric breakdown voltage was determined by placing a sample of the separator between two stainless steel pins, each 2 cm in diameter and having a flat circular tip, and applying an increasing voltage across the pins using a Quadtech Model Sentry 20 hipot tester, and recording the displayed voltage (the voltage at which current arcs through the sample).
- Tensile elongation (elongation to break) was determined using an Instron Model 1123 Universal Tester according to ASTM D882-02. Samples were cut to 0.50 inches (1.27 cm) by 1.75 inches (4.45 cm). The initial jaw separation was 1 inch (2.54 cm) and the strain rate was 2 inches (5.08 cm) per minute. Tensile elongation was calculated by subtracting the initial sample length from the sample length at break, dividing the remainder by the initial sample length and multiplying the dividend by 100 percent.
- Area Specific Resistance (ASR) was determined for separator samples suspended in an electrolyte between two platinum electrodes, using a Model 34 Conductance-Resistance Meter from Yellow Springs Instrument, Yellow Springs, OH, USA, to make resistance measurements. The electrolyte solution used was 9.14 weight percent LiI salt in a solvent blend of 1,3-dioxolane, 1,2-dimethoxyethane and 3,5-dimethylisoxazole (63.05 : 27.63 : 0.18 by weight). All testing was done in an atmosphere of less than 1 part per million of water and less than 100 parts per million of oxygen. An electrically nonconductive sample holder, designed to hold the separator sample with a 1.77 cm² area of the separator exposed, was submerged in the electrolyte solution so that the portion of the holder for holding the sample lay halfway between two platinum electrodes, 0.259 cm apart. The resistance between the electrodes was measured. The holder was removed from the electrolyte, a separator sample inserted in the holder, and the holder was slowly lowered into the electrolyte solution to the same set level so that the sample was completely flooded with electrolyte with no gas bubbles entrapped in the sample. The resistance was measured. The ASR was calculated using the formula:

$$ASR = A (R_2 - R_1 + \rho L/A)$$

where A is the area of the exposed separator sample, R₂ is the resistance value with the film present, R₁ is the resistance value without the film, L is the separator sample thickness and ρ is the conductivity of the electrolyte used.

- Specific surface area was determined by the BET method, using a TriStar gas adsorption analyzer from Micromeritics Instrument Corporation, Norcross, GA, USA. A sample of 0.1 g to 0.2 g of the separator was cut into pieces of less than 1cm² to fit the sample holder, the sample was degassed under a stream of nitrogen at 70°C for 1 hour, and a pore size distribution analysis was performed using nitrogen as the adsorbant gas and collecting full adsorption/desorption isotherms.

It will be understood by those who practice the invention and those skilled in the art that various modifications and improvements may be made to the invention without departing from the spirit of the disclose concept. The scope of protection afforded is to be determined by the claims and by the breadth of interpretation allowed by law.